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UNITED STATES DEPARTMENT OF AGRICULTURE  
SOIL CONSERVATION SERVICE  
WASHINGTON, D. C.



**MEASUREMENTS OF THE FALL-VELOCITIES OF  
WATER-DROPS AND RAINDROPS**

By  
J. Otis Laws  
Assistant Soil Conservationist

C. E. Ramser, Chief  
Hydrologic Division  
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MEASUREMENTS OF THE FALL-VELOCITY OF  
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J. Otis Laws

INTRODUCTION

This paper presents measurements of the velocities of water-drops of sizes ranging from 1 to 6 mm in diameter, falling in still air from heights of 0.5 to 20 meters. A few measurements of rain-drop velocities are also reported.

These measurements were undertaken to assist in an understanding of the action of rain, both real and artificial, in eroding soil. The drop sizes of rains have also been measured and will be reported separately. All of these studies were carried out at the Hydraulic Laboratory of the National Bureau of Standards as a part of the work of the Soil Conservation Service.

The velocity of falling raindrops and water-drops has been studied by several investigators in the past. The most complete measurements are those of P. Lenard (1) and Wilhelm Schmidt (2) (see "References" at end of paper).

Lenard measured the velocities of drops of 1.23 to 6.36 mm diameter by suspending them in the blast of a fan and measuring the air velocity at the point of suspension. He measured the size by catching the drops on a sheet of absorbent paper as they slipped out of the air stream. From the size of the water spot he determined the size of the drop, following the method of drop size

measurement used by most European observers. Defant (3) made the most thorough study of this method of drop size measurement.

Schmidt measured the velocity of raindrops varying in size from 0.4 to 3.5 mm diameter with an ingenious apparatus consisting of two discs mounted on an axle and turned at a known rate. A raindrop, which by chance fell through a small sector cut in the upper disc, would land upon a piece of absorbent paper laid on the lower disc and turning with it. The location of the spot relative to the projection of the sector on the paper gave a measure of the velocity, while the diameter of the spot gave a measure of the drop size.

H. Mache (4) made a few measurements photographically but he had no way of finding the size of the drops whose velocity he measured. Mache's work deserves mention primarily because a modification of his method was used in the present measurements.

The measurements reported here were undertaken primarily to obtain data on the velocities of drops falling through the relatively small distances that it is practicable to use in producing artificial rains. The data gathered on raindrops served as a direct check upon the measurements of Schmidt. The indoor measurements at heights of fall where the velocity can be regarded as terminal offer a check upon Lenard's measurements.

The measurements reported here show a surprisingly large deviation from the measurements of Lenard and Schmidt, whose results

closely confirmed each other. Velocities fully 15 percent higher were observed. Finding no appreciable errors in the present measurements, it is the author's conclusion that the values observed nearly 30 years ago and accepted unquestioningly since, are in error by large amounts.

#### METHODS OF MEASUREMENT

Camera and Light Box: The measuring apparatus consisted of a 9 x 12 cm still camera mounted behind a "chopper disc", driven by a small synchronous motor. In front of this a collimating lens was mounted at a distance equal to its focal length from the center of the camera lens. This had the effect of making objects on the other side of the collimating lens appear the same size regardless of their distance from the camera. Dark field illumination was accomplished by a light box employing over run lamps arranged in such a way that light was directed toward the camera from either side on the field of view. Strips of sheet metal were placed in front of the collimating lens to reduce the amount of light absorbed on its surface. An opening of 4 x 5 inches was left in the light box for drops to fall through. The camera side of the collimating lens was shielded from the light of the room by a conical casing.

The use of dark field illumination and a "chopper disc" made it possible to obtain multiple images of a drop on a single film. The arrangements of the light and the camera are shown in the accompanying schematic diagram.



# DROP VELOCITY CAMERA

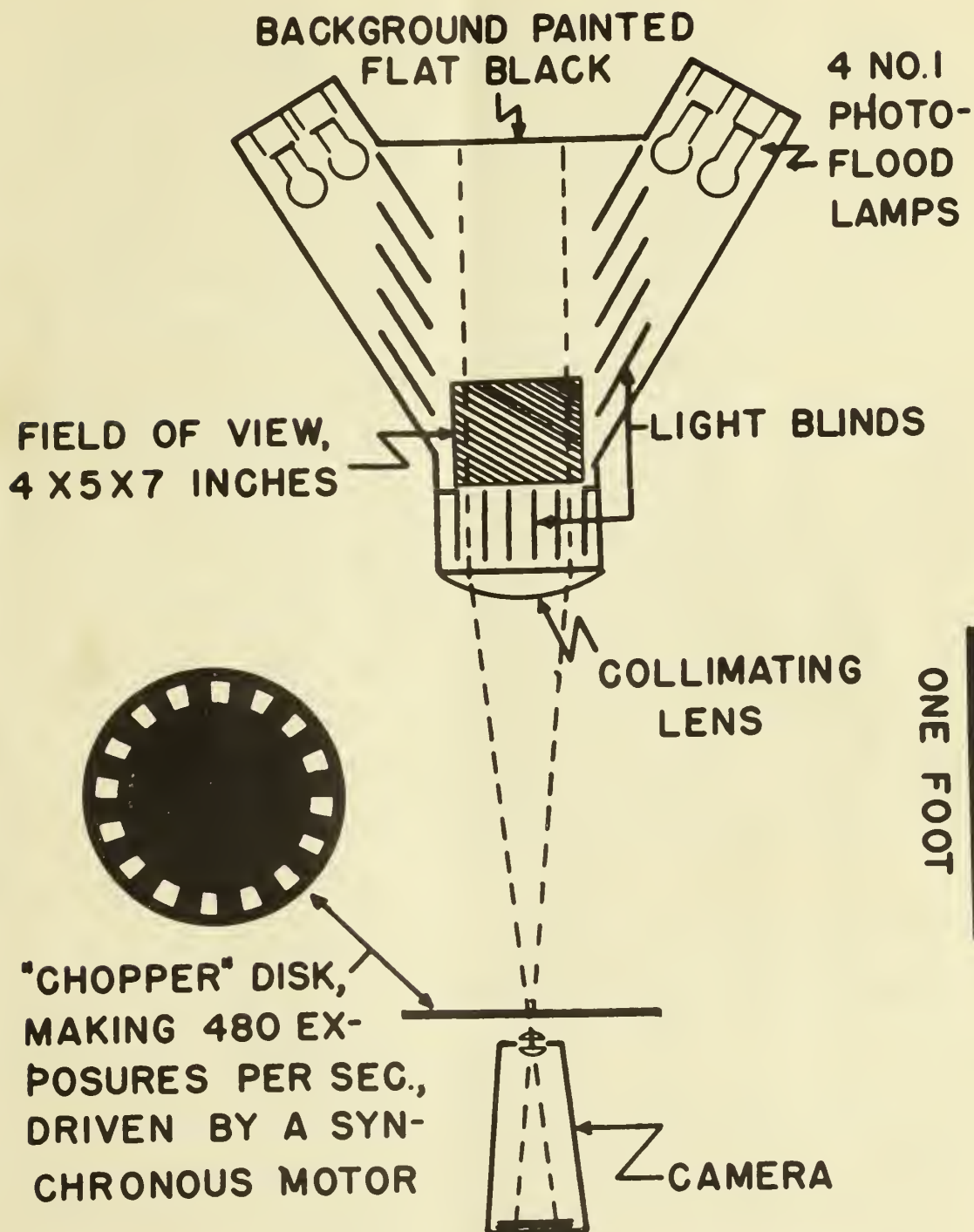


**Figure 1.** The velocities of the drops were measured by means of a still camera fitted with a rotating disc shutter driven by a synchronous motor and making 480 exposures per second. Dark field illumination was employed, and a collimating lens was interposed between the subject and the camera to eliminate magnification errors.



Magnification Error: The magnification of the combined lenses was determined by photographing a millimeter ruled cross-section paper in the center of the camera field, the paper being held between two glass plates in a plane normal to the camera's axis. The accuracy of the rulings was checked just before photographing. Measurements from the developed film by means of a micrometer microscope showed the magnification in the center of the field to be  $1/2.544$ .

The magnification at different positions in the field was determined by the same method with the following results: magnification  $1/2$  inch from the light side of the opening-- $1/2.548$ , magnification  $3\ 1/2$  inches from the light side of the opening-- $1/2.539$ . The maximum error, therefore, to be expected from this source is about 0.2%, which was considered sufficiently accurate although the optical system was capable of even greater precision. If the collimating lens had not been used the deviation from the average magnification would have been 8%.

Mr. J. M. Slater (5) who suggested the use of such an optical system has described the optical characteristics of similar systems in a recent issue of Photo Technique.

The Shutter: The timing device was a single phase  $1/150$  horsepower synchronous motor which turned at 30 r.p.s. on a 60 cycle alternating current. The motor was plugged into the lines of the Potomac Electric Power Company. The generators of this company are tied in with the so-called "eastern system". The frequency of this current is carefully regulated and believed to be constant within a

few tenths of a percent. To ascertain whether the motor, for any cause, was not turning in synchronism with the current when the "chopper disc" was mounted, the motor was placed in a dark room and illuminated by a neon lamp, under which illumination the screw heads of the hub appeared to be stationary, which would only occur when the motor was turning in synchronism with the current. It was observed that considerable braking force had to be exerted before the motor "lost step" as indicated by an apparent slow counter rotation of the screw heads.

The "chopper disc" was made from a paper chart designed for use on a water stage recorder. Out of this circular sheet, which was  $11 \frac{1}{8}$  inches in diameter, 16 sectors were cut  $\frac{1}{4}$  inch from the rim, each sector measuring  $1 \times \frac{7}{8}$  inches. Both sides of the sectors were carefully cut along the printed radii of the chart. The disc was then painted black.

Taking the Picture: To take a picture with this apparatus, the motor was started, the lights were turned on, and the camera shutter was opened for a short interval of time. It was desirable to have as many drops as possible on a single negative, but if the exposure was too prolonged the light absorbed on the imperfectly shielded collimating lens obscured the drop image. For this reason, an exposure of approximately 2 seconds was the maximum that could be used.

The aperture opening was set at  $f/8$ . The film used was Agfa Super Pan Press. It was developed for maximum contrast.

Measuring Velocity from Negative: The image of each drop appeared as a pair of broken lines, see figure 2. The partitions in the "chopper disc" obstructed the light many times during the drop's passage through the illuminated dark field. The two lines of the image were due to high lights which appeared on either side of the drop.

To determine the velocity, the distance between the tips of two drop images was measured. The points of a pair of dividers were fitted to two images on the negative as far apart as possible; the "drop negative" was then replaced by a negative of the cross-section paper. The distance,  $h$ , as indicated by the points of the dividers was read to the closest half millimeter. The number,  $n$ , of breaks in the double line were then counted. Since the motor turned at 30 r.p.s. and the "chopper disc" had 16 openings, the film was exposed  $30 \times 16 = 480$  times a second, or the time elapsed between the points of measurement is  $t = n/480$ . Therefore, the average velocity over this interval is  $v = h/t = 480 h/n$ . A correction for a slight error in the ruling of the cross-section paper photographed and used as standard of measurement was thrown into the coefficient, and the actual formula used in computing the velocity was  $v = 4.81 h/n$ . When  $h$  is expressed in centimeters this formula gives the velocity in meters per second.

Measuring Diameter from the Negative: The precise determination of the diameter of the drop from the negative proved to be impossible. The high lights on either side of the drop produced an halation on the film that varied with position in the field, velocity, and possibly, exposure, development, etc. Although several schemes of



# TYPICAL VELOCITY PHOTOGRAPH

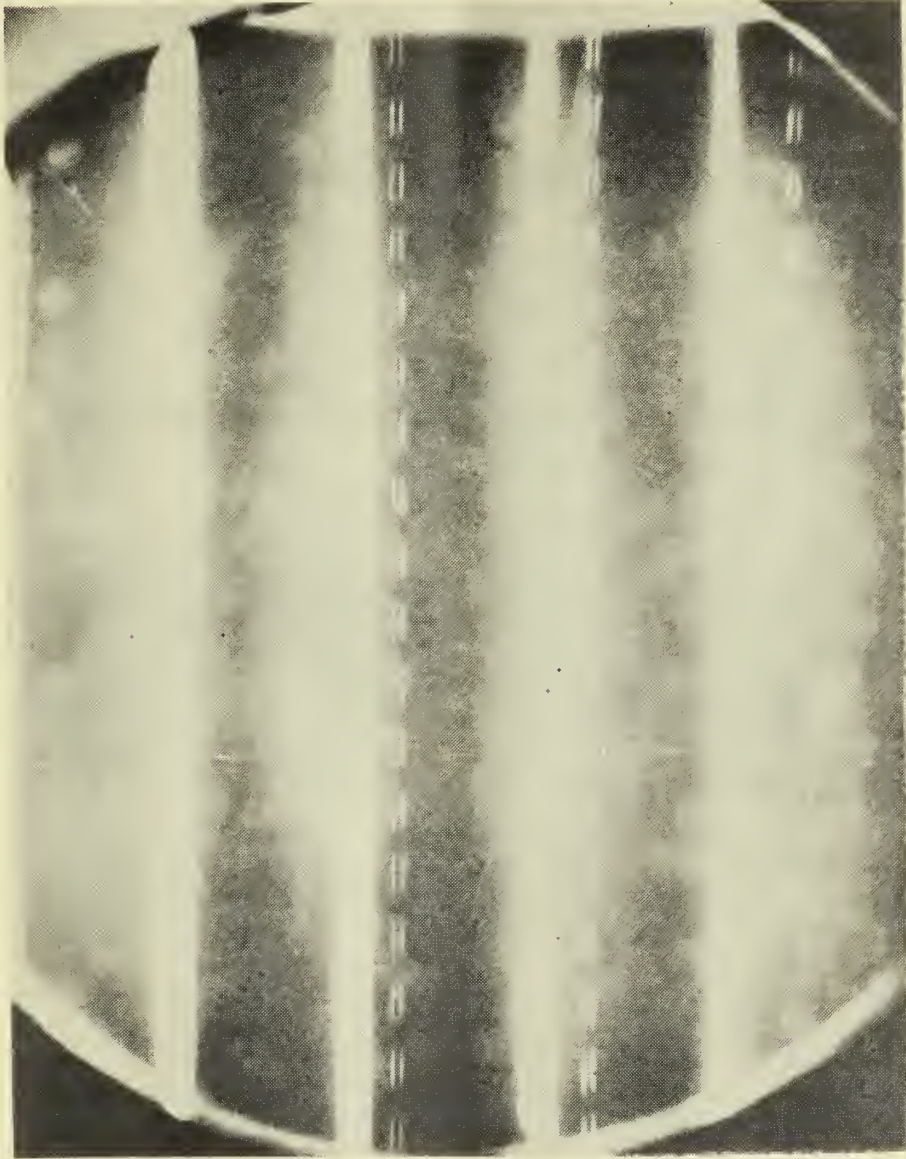


Figure 2.

In the above typical photograph obtained with this camera the light blinds immediately in front of the collimating lens appear as bright vertical streaks. The broken double lines were blurred images of falling drops, the drops having moved during the exposure. Each drop produces a double line image due to the manner in which it was illuminated.



measurement were tried, none was found that gave consistent results within the rather narrow limits necessitated by this study. This unexpected short-coming of the apparatus severely limited its utility, in so far as it necessitated the use of independent methods of measuring the drop size.

Independent Measurement of Drop Size: This measurement was accomplished by allowing water to drip from glass tubes of small diameter, made by heating and drawing out glass tubing. Such a capillary was fitted to a filtering flask which was suspended above the raindrop camera and the flow through the dripping tube was controlled by a screw clamp. Drops were allowed to fall as fast as they could be conveniently counted--from two to three drops per second. Immediately before taking a photograph, a weighing bottle was placed under a capillary and 10 to 30 drops were collected. These were weighed on an analytical balance and the mass of the average drop was computed. Evaporation from the weighing bottle was checked and corrections were applied when necessary.

By this means drops ranging from 1.17 to 6.1 millimeters were obtained. The production of drops smaller than 3 millimeters by this method necessitated the use of extremely small aperture, and pressure often had to be applied to the filtering flask. To prevent the drops from wetting the outside of the tube and to decrease the friction along the tube walls, the inside and outside of these capillary tubes were coated with a thin layer of paraffin. This was accomplished by applying a vacuum to the capillary and dipping it momentarily into molten paraffin.

Before this later technique was developed a number of measurements were made of drops of 2.3 millimeter diameter by forcing water through an uncoated capillary at a high rate of dripping-- 8 to 15 drops per second. In order to determine the drop size under these conditions the rate of dripping was determined by passing a piece of blotting paper under the capillary for a given interval of time and counting the number of spots. The weighing bottle was then placed under the capillary for a measured interval of time. These measurements were not precise and the drops seemed to vary in size. A disproportionate variability appears in the data obtained by this method (see figure 5-b).

The usual procedure for measuring drop size did not give exactly the right value for the 6 mm drops, due to a secondary drop which is produced at the instant of breaking away from the capillary and which fell into the weighing bottle along with the principal drops. Their size was roughly determined from measurements on the film, and a correction was applied although it amounted to less than 1%.

Unreported Measurements of Very Small Drops: Several measurements were made of sprays composed of small drops but in these measurements no precise data were obtainable on their size. These measurements were not considered sufficiently exact to report.

Adaptation of Apparatus to Measurement of Raindrop Velocities: In order to adapt this photographic apparatus to the measurement of velocities of raindrops, a means had to be provided for measuring the size of the individual drops photographed. A shelter was built on

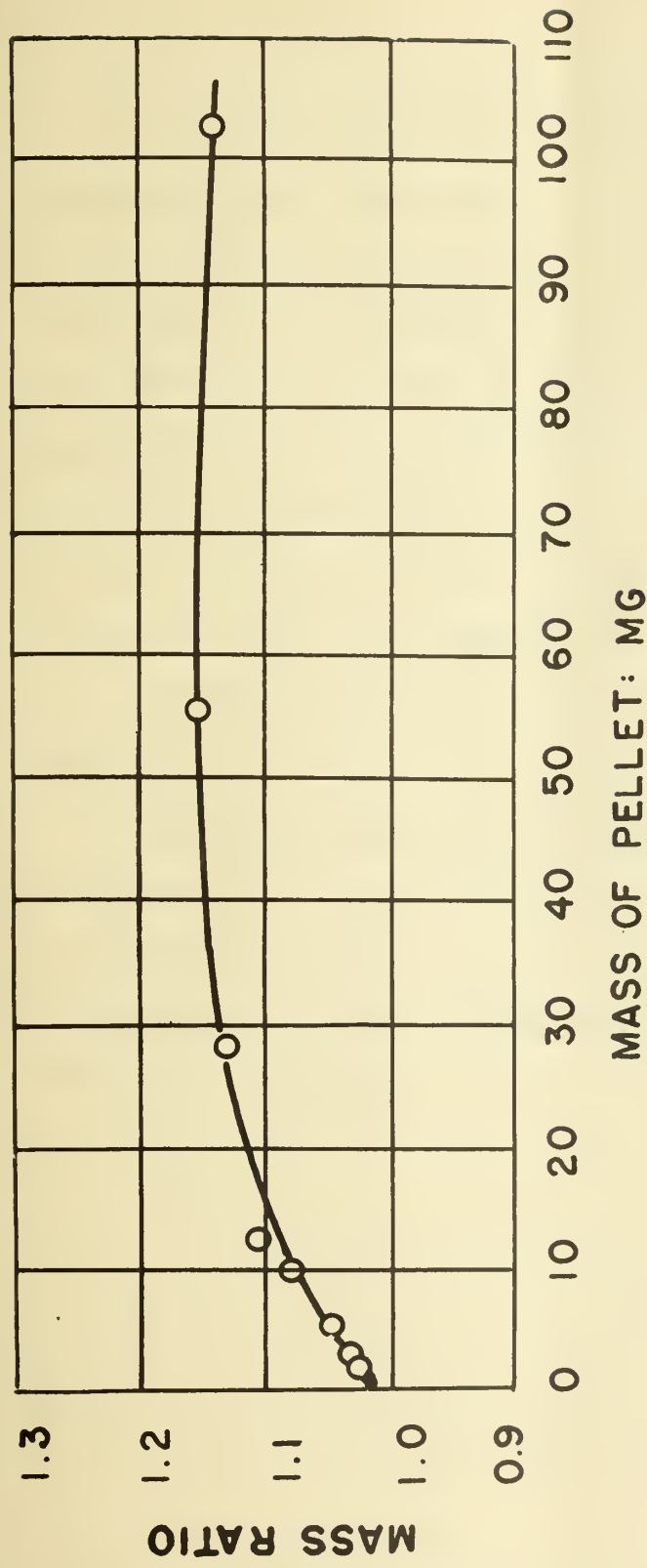
the roof of the Hydraulic Laboratory, and the camera and its light box were placed directly under a 4 x 5 inch opening in the roof of this shelter. The opening was insulated from splashes by grill work extending one foot out in all directions and was provided with a cover which could be removed by the operation of a lever extending inside the shelter.

The camera and the light box were provided with a broad belt with apertures so arranged that, by drawing this belt across the opening in the light box, the camera field could be briefly exposed to the rain and, with the same movement, the film could be exposed. The apertures in the belt were so spaced that no drop could pass through the field without the film being exposed to it. A pan of uncompacted and calibrated flour was placed under the light box in a position to catch any drop that fell through the camera's field. By drying and weighing the pellets of dough, formed by the drops in the flour, the size of the drops themselves could be calculated. See figure 3. (This technique of drop size measurement was first used by Bentley (6). The details of making such size measurement will be discussed in a separate paper.)

If the camera's field was not too long exposed to the rain, the few pellets found in the flour could be associated with the impressions found on the negative by the size and location of each. When too many drops fell through, the association of pellets and impressions became dubious and the film had to be discarded.



# CALIBRATION OF FLOUR



$$\text{MASS RATIO} = \frac{\text{MASS OF DROP}}{\text{MASS OF PELLET}}$$

Figure 3. The above relationship was found to apply to the Gold Medal flour used in these measurements. It was determined by allowing water to drip from small glass tubes into a pan of the flour. The size of the artificial drops was determined by catching a counted number and weighing. The air-dry pellets were desiccated for 60 minutes at 110° C. The relationship varies slightly from one sack of flour to the next of the same brand.



Successful measurements could only be made on fairly large raindrops falling nearly vertical. All drops approaching the apparatus from angles greater than  $30^{\circ}$  fell outside the camera's field. Single pellets of drops smaller than 2 or 3 mm were difficult to weigh with sufficient precision. The chief limitation of this arrangement was the time required to obtain data on adequate range of sizes. While many large drops were present in some of the rains photographed, we were not fortunate enough to capture them in the extremely small samples peculiar to this apparatus.

The vertical components of the velocities are reported in Figure 6.

Hygrometric Measurements: Hygrometric and barometric data were taken in conjunction with most of the indoor measurements. Wet and dry bulb temperatures were read from a sling psychrometer. The atmospheric pressure was determined by an aneroid barometer at the elevation of the camera.

## TEST RESULTS

Indoor Measurements: The results of the indoor measurements are presented in table 1, where they are arranged in ascending order of drop size and height of fall. These data have been plotted in figures 5-a and 5-b.

It was not always possible to obtain drops of exactly the same size. This necessitated drawing curves through data points that are not strictly comparable. The drop size represented by the curve is recorded along the curve.

In the summarization of these data a theoretical frame-work would be most useful; its derivation, however, is difficult. The general problem, of which this study is merely a special case, is that of expressing the resistance to motion encountered by an immersed body. A concise review of the more important work done on this problem from Newton to present day investigators has been made by Rouse (7) in his "Nomogram for the Settling Velocity of Spheres."

The deduction of a formula applicable to water-drops is complicated by the change in shape that the larger drops undergo during their fall. A falling water-drop is not tear-shaped, as is now well known, but quite oblate at terminal velocity as shown by the experiments of Lenard, loc. cit., as well as by some photographs of Professor Edgerton (12) of the Massachusetts Institute of Technology. During the first few meters of fall a large drop vibrates between vertical and horizontal oblateness with a frequency that depends upon its size. This oscillation is shown, quite incidentally, in



Figure 4. This is a photograph of a large waterdrop falling through still air. It was taken by H. E. Edgerton and confirms the observations of previous investigators who concluded that falling drops were flattened rather than "streamlined" as commonly supposed.



Worthington's (8) remarkable photographs.

The frequency of the vibration of a water-drop was studied by Lord Rayleigh (9) who found  $4/D^2$  oscillations per second where  $D$  is the diameter of the drop in inches.

The effect of this change in shape is to add a new order of variation to a phenomenon already beyond the reach of current analytical tools. If the shape of the drop had been ascertainable from the photographs, it might have been possible to find an empirical relation between the coefficient of the resistance formula and the Reynolds number. The computation of this number, however, requires a knowledge of the horizontal diameter of the drop and, therefore, the development of such an empirical formula, which would have served as a basis for comparing the data obtained under the various conditions, was not possible.

The original purpose of these measurements does not justify an extended rational investigation, but it is hoped such a study may sometime be attempted. With a view of assisting such an endeavor, the hygrometric and barometric data have been included in table 1. Liznar's (10) analysis of the data of Lenard and Schmidt is a good starting point for this study.

Lacking satisfactory rational equations, the data have been very simply presented in graphical form. Figure 7 shows the relation between velocity and diameter for various heights of fall. These curves were obtained by reading off values from the smooth curves of figure 5. Table 2, in turn, has been prepared from figure 7. Attempts to extend table 2 to include smaller drop sizes encountered

complexities similar to those discussed above, and it was thought best to confine the table to the range of experimentally determined values.

Measurements of Raindrop Velocities: The few observations gathered on the velocities of raindrops have simply been plotted in figure 6 and are not tabulated. A curve representing the values of Lenard and Schmidt as well as the curve representing the velocities observed indoors after 20 meters fall, have been plotted on the same figure of comparison. The values represent the vertical component of the actual raindrop velocities.

The tendency for the velocities of raindrops falling from great heights to be lower than the velocities of water-drops falling from only 20 meters indoors, may be due to the turbulence of the atmosphere through which the raindrops pass. The stray points appearing in the figure are probably the result of having incorrectly paired pellets and drop images.

The velocities found by Lenard and Schmidt are evidently much too low. The low velocities observed by Lenard may be due to excessive turbulence in the air stream he used. Schmidt's method of measuring drop size is open to question. In calibrating his absorbent paper, he appears to have overlooked the effect of height of fall upon the relation between spot diameter and drop diameter. This oversight was not as important in Lenard's measurements where the velocity of the drops relative to the paper was small.

Possible Sources of Error in the Present Measurements: In attempting to explain the discrepancy between the velocity measurements

presented here and those of Lenard and Schmidt, the technique of measurement employed in this present study has been examined from many angles. Film shrinkage, motor speed and magnification were checked and no appreciable error was found.

Evaporation from the drop surface was also investigated. A few measurements of evaporation were attempted on large drops falling 15 meters. The drop size was measured at the dripping tube by the usual method, and immediately afterward the drops were caught 15 meters below in a two-quart jar in the bottom of which several inches of flour had been placed to cushion the impact of the drops. This jar was capped and the drops were again weighed. No evaporation was detected in these crude measurements.

A study of evaporation by two Japanese is helpful in estimating the magnitude of this error. Namakawa and Takahashi (11) studied the evaporation of small water-drops in air and found the following formula:

$$\frac{dR}{dt} = -\frac{\rho}{R} \cdot \frac{0.623 \rho M}{B} (P_1 - P_0)$$

where  $R$  = radius of drop;  $t$  = time;  $\rho$  = density of dry air;  $M$  = molecular diffusion constant;  $B$  = barometric pressure;  $p_1$  = saturation pressure at the temperature of the evaporating surface;  $P_0$  = vapor pressure at the temperature and humidity of the air; and  $\rho$  = a function of the velocity of the drop relative to the air. C.G.S. units were employed. The value of  $\rho$  was determined for drops of  $R = .085$  cm for several velocities up to 2 m/sec. The results

were expressed in the following empirical equations:

$$\rho' = 1 + 0.21\sqrt{v}$$

the velocity,  $v$ , being expressed in meters per second.

Due to the limited velocities used in their experiments a bold extrapolation must be made in applying these results to our problem. If such an extrapolation is justifiable, the Namakawa formula indicates that the evaporation occurring in a few seconds of fall is negligible. The change in diameter calculated for a 1.74 mm drop after 2 seconds of fall was less than 0.1%.

Height of Fall Required to Attain Terminal Velocity: The question is often asked, "How far must a drop fall to reach a constant velocity?" Curves drawn to fit the experimental data approach the terminal value gradually, and it is difficult to decide at precisely what height they become coincident with the terminal value. The height required for drops to attain 95% of their terminal velocity can be found with greater exactness and, for most purposes, should serve just as well. These heights of fall, as derived from the curves of figure 5, are:

|           |      |            |
|-----------|------|------------|
| 1 mm drop | ---- | 2.2 meters |
| 2 mm drop | ---- | 5.0 meters |
| 3 mm drop | ---- | 7.2 meters |
| 4 mm drop | ---- | 7.8 meters |
| 5 mm drop | ---- | 7.6 meters |
| 6 mm drop | ---- | 7.2 meters |

It will be observed that the 5 and 6 mm drops attain 95% of their terminal velocity after shorter distances of fall than is required by the 4 mm drop. Evidently, the necessary height of fall does not always increase with increasing drop size. This is also true when the heights are read at 98% of the terminal velocity and

the trend doubtless applies also to the height required to attain the full terminal velocity.

Explanation of Why Large Drops Attain Terminal Velocities Sooner than Medium-size Drops: This phenomenon is believed to be related to the apparent over-shooting of the terminal velocity observed in the 6.1 mm drop; see figure 5. It is too curious to be left without some attempt being made at explanation.

It will be observed that the 6.1 mm drop appears to approach finally a terminal value of 9.30 m/sec. after about 20 meters fall. Drops of this size, however, were observed to be falling at the same velocity after only 10.5 meters fall. In the intervening distance, a drop of this size apparently increases in velocity until it attains a maximum of 9.40 m/sec. at about the 14th meter, after which height it gradually slows down.

If this slowing down is real--and it appears to be--it is evident that the drop must have required time to attain its final shape. For, if changes in shape occurred concurrently with changes in velocity, the final value of air resistance would have been acting on a drop of this size after 10.5 meters fall, and this force of resistance being equal and opposite to the force of gravity, would reduce the resultant force to zero. The drop would then have continued in a state of uniform motion.

Since the velocity of the drop continued to increase, its shape must have been such that it offered less resistance at 10.5 meters than it did at 20 meters, in spite of the fact that its

velocity relative to the air was the same at both heights. It must be concluded, therefore, that changes in shape do not occur concurrently with changes in velocity, but that time is required for a given relative air velocity to produce the final drop shape corresponding to that velocity.

Lenard's observations led him to a similar conclusion. He writes, "It can be seen that they (large drops suspended in upward air currents produced by a fan) are considerably deformed. The deformation flattens the drop vertically; this often continues in the large drops to a point where breaking-up occurs. Prior to this I have observed a similar deformation in natural rain by means of instantaneous illumination. The drops of the previous test showed no such deformation. It appears, therefore, that this deformation requires more time than was allowed in the previous tests where less than a tenth of a second elapsed. This corroborates the fact that the flattening of large suspended drops, in which the deformation occurs, begins only after an appreciable stay in the moving air.

"This time lag is understandable if the deformation is not the result of pressure directed perpendicular to the drop surface but of a tangential friction force of the air that brings the whole mass of the drop into circulatory motion which can only happen slowly because of the relatively large inertia of the water."

If such a lag is present, the reason why the large drops attain their terminal velocities at such small distances of fall is

obvious. During the early stages of their fall, the large drops tend to remain spherical and, thus offering a smaller cross-sectional area to the passing air, attain, after small distances of fall, velocities higher than those consistent with their final shape. In the case of very large drops, the terminal velocity is actually exceeded. In drops of 5 mm, the terminal velocity is apparently never exceeded, but it is attained very early. This tendency is also evident in the 4 mm drop, although less striking. The smaller drops are less easily deformed, and approach their terminal values of velocity more evenly.



TABLE 1

Test Data

D = diameter of a sphere equal in volume to the drop

H = height of fall

v = velocity of fall

t = temperature of air (dry bulb)

t' = wet bulb temperature

B = barometric pressure

$\nu$  = kinematic viscosity of air

| D<br>mm.  | H<br>meters | V<br>m/sec. | t<br>°C | t'<br>°C | B<br>mmHg | $\nu$<br>(cm <sup>2</sup> /sec.) |
|-----------|-------------|-------------|---------|----------|-----------|----------------------------------|
| 1.15-1.19 | 0.53        | 2.74        | 21.0    | 13.3     | 752       | .153                             |
| "         | 0.98        | 3.48        | "       | "        | "         | "                                |
| "         | "           | 3.47        | "       | "        | "         | "                                |
| "         | "           | 3.44        | "       | "        | "         | "                                |
| "         | 1.50        | 3.87        | "       | "        | "         | "                                |
| "         | 2.50        | 4.28        | "       | "        | "         | "                                |
| "         | 4.50        | 4.60        | "       | "        | "         | "                                |
| 1.74      | 0.50        | 2.84        | 23.0    | 15.3     | 748       | .156                             |
| "         | "           | 2.85        | "       | "        | "         | "                                |
| "         | 1.50        | 4.36        | "       | "        | "         | "                                |
| "         | "           | 4.38        | "       | "        | "         | "                                |
| "         | 2.5         | 5.12        | "       | "        | "         | "                                |
| "         | 3.46        | 5.49        | "       | "        | "         | "                                |
| 1.73      | 4.5         | 5.69        | "       | "        | "         | .151                             |
| "         | 6.0         | 5.86        | "       | "        | "         | "                                |
| "         | 8.0         | 5.90        | "       | "        | "         | "                                |
| 2.28      | 0.5         | 2.94        | 25.0    | 19.5     | 764       | .155                             |
| "         | "           | 2.94        | "       | "        | "         | "                                |
| "         | 1.0         | 3.93        | "       | "        | "         | "                                |
| "         | "           | 3.95        | "       | "        | "         | "                                |
| 2.29      | 1.18        | 4.33        | 21.7    | 10.6     | 763       | .152                             |
| "         | "           | 4.33        | "       | "        | "         | "                                |
| "         | "           | 4.31        | "       | "        | "         | "                                |
| "         | "           | 4.31        | "       | "        | "         | "                                |
| 2.28      | 1.5         | 4.67        | 25.0    | 19.5     | 764       | .155                             |
| "         | "           | 4.67        | "       | "        | "         | "                                |
| 2.29      | 1.89        | 5.10        | 21.7    | 10.6     | 763       | .152                             |
| "         | "           | 5.08        | "       | "        | "         | "                                |
| "         | "           | 5.12        | "       | "        | "         | "                                |
| "         | "           | 5.12        | "       | "        | "         | "                                |
| "         | "           | 5.05        | "       | "        | "         | "                                |
| "         | "           | 5.05        | "       | "        | "         | "                                |

TABLE 1 (Continued)

| D<br>mm | H<br>meters | v<br>m/sec. | t<br>°C | t'<br>°C | B<br>mm Hg | $\nu$<br>(cm <sup>2</sup> /sec.) |
|---------|-------------|-------------|---------|----------|------------|----------------------------------|
| 2.28    | 2.0         | 5.15        | 25.0    | 19.5     | 764        | .155                             |
| "       | "           | 5.14        | "       | "        | "          | "                                |
| "       | "           | 5.13        | "       | "        | "          | "                                |
| "       | 2.5         | 5.53        | "       | "        | "          | "                                |
| "       | "           | 5.49        | "       | "        | "          | "                                |
| 2.38    | 2.81        | 5.72        | 21.7    | 10.6     | 763        | .152                             |
| "       | "           | 5.80        | "       | "        | "          | "                                |
| "       | "           | 5.66        | "       | "        | "          | "                                |
| 2.28    | 3.0         | 5.83        | 25.0    | 19.5     | 764        | .155                             |
| 2.28    | 3.5         | 6.05        | "       | "        | "          | "                                |
| 2.38    | 3.71        | 6.21        | 21.7    | 10.6     | 763        | .152                             |
| "       | "           | 6.23        | "       | "        | "          | "                                |
| "       | "           | 6.23        | "       | "        | "          | "                                |
| "       | "           | 6.18        | "       | "        | "          | "                                |
| "       | 4.68        | 6.36        | "       | "        | "          | "                                |
| "       | "           | 6.47        | "       | "        | "          | "                                |
| "       | "           | 6.50        | "       | "        | "          | "                                |
| "       | "           | 6.28        | "       | "        | "          | "                                |
| 2.32    | 5.51        | 6.66        | 24.0    | 15.9     | 761        | .154                             |
| "       | "           | 6.66        | "       | "        | "          | "                                |
| "       | "           | 6.64        | "       | "        | "          | "                                |
| 2.34    | 6.51        | 7.06        | "       | "        | "          | "                                |
| "       | "           | 7.03        | "       | "        | "          | "                                |
| "       | "           | 7.03        | "       | "        | "          | "                                |
| "       | 7.50        | 6.92        | "       | "        | "          | "                                |
| "       | 8.56        | 7.06        | "       | "        | "          | "                                |
| "       | 10.8        | 7.06        | "       | "        | "          | "                                |
| "       | 11.2        | 7.06        | "       | "        | "          | "                                |
| "       | 13.0        | 7.07        | "       | "        | "          | "                                |
| "       | "           | 7.08        | "       | "        | "          | "                                |
| "       | "           | 7.08        | "       | "        | "          | "                                |
| 3.02    | 0.24        | 2.12        | ---     | ---      | ---        | ---                              |
| "       | "           | 2.12        | ---     | ---      | ---        | ---                              |
| "       | "           | 2.13        | ---     | ---      | ---        | ---                              |
| "       | 0.50        | 2.96        | ---     | ---      | ---        | ---                              |
| "       | "           | 2.98        | ---     | ---      | ---        | ---                              |
| "       | "           | 3.01        | ---     | ---      | ---        | ---                              |
| "       | "           | 2.97        | ---     | ---      | ---        | ---                              |
| 3.08    | "           | 3.04        | 23.6    | 15.0     | 756        | .151                             |
| "       | "           | 3.03        | "       | "        | "          | "                                |
| "       | "           | 3.04        | "       | "        | "          | "                                |
| "       | "           | 3.05        | "       | "        | "          | "                                |

TABLE 1 (Continued)

| D<br>mm | H<br>meters | v<br>m/sec. | t<br>°C | t'<br>°C | B<br>mm Hg | $\nu$<br>(cm <sup>2</sup> /sec.) |
|---------|-------------|-------------|---------|----------|------------|----------------------------------|
| 3.02    | 0.97        | 4.09        | ---     | ---      | ---        | ---                              |
| "       | "           | 4.07        | ---     | ---      | ---        | ---                              |
| "       | "           | 4.07        | ---     | ---      | ---        | ---                              |
| 3.08    | 1.0         | 4.13        | 23.6    | 15.0     | 756        | .153                             |
| "       | "           | 4.13        | "       | "        | "          | "                                |
| "       | "           | 4.16        | "       | "        | "          | "                                |
| "       | "           | 4.15        | "       | "        | "          | "                                |
| 3.05    | 1.05        | 4.18        | 25.0    | 21.9     | ---        | ---                              |
| "       | 1.50        | 4.79        | "       | "        | ---        | ---                              |
| 3.08    | 2.02        | 5.40        | "       | "        | ---        | ---                              |
| "       | "           | 5.45        | "       | "        | ---        | ---                              |
| "       | "           | 5.40        | "       | "        | ---        | ---                              |
| "       | 2.50        | 5.73        | "       | "        | ---        | ---                              |
| "       | "           | 5.80        | "       | "        | ---        | ---                              |
| "       | 3.01        | 6.13        | "       | "        | ---        | ---                              |
| "       | "           | 6.14        | "       | "        | ---        | ---                              |
| "       | 3.50        | 6.53        | "       | "        | ---        | ---                              |
| "       | "           | 6.43        | "       | "        | ---        | ---                              |
| "       | 3.79        | 6.61        | "       | "        | ---        | ---                              |
| "       | "           | 6.07        | "       | "        | ---        | ---                              |
| 3.02    | 4.02        | 6.74        | 21.0    | ---      | 755        | ---                              |
| "       | "           | 6.79        | "       | ---      | "          | ---                              |
| "       | "           | 6.79        | "       | ---      | "          | ---                              |
| "       | 4.50        | 7.00        | 20.7    | ---      | 744        | ---                              |
| "       | "           | 7.00        | "       | ---      | "          | ---                              |
| "       | "           | 7.00        | "       | ---      | "          | ---                              |
| "       | 5.04        | 7.16        | 21.0    | ---      | 755        | ---                              |
| "       | "           | 7.16        | "       | ---      | "          | ---                              |
| "       | "           | 7.16        | "       | ---      | "          | ---                              |
| "       | 5.49        | 7.22        | "       | ---      | "          | ---                              |
| "       | 6.00        | 7.43        | "       | ---      | "          | ---                              |
| "       | "           | 7.42        | "       | ---      | "          | ---                              |
| "       | 6.50        | 7.49        | "       | ---      | "          | ---                              |
| "       | "           | 7.51        | "       | ---      | "          | ---                              |
| "       | 7.00        | 7.57        | "       | ---      | "          | ---                              |
| "       | 7.50        | 7.70        | 20.7    | ---      | 744        | ---                              |
| "       | 8.00        | 7.79        | "       | ---      | "          | ---                              |
| "       | "           | 7.82        | "       | ---      | "          | ---                              |
| "       | "           | 7.82        | "       | ---      | "          | ---                              |
| 3.00    | 10.00       | 7.90        | 24.8    | 21.2     | 756        | .156                             |
| "       | "           | 7.82        | "       | "        | "          | "                                |
| "       | 12.00       | 7.94        | "       | "        | "          | "                                |
| "       | "           | 7.96        | "       | "        | "          | "                                |
| "       | 14.00       | 8.08        | "       | "        | "          | "                                |
| "       | "           | 8.03        | "       | "        | "          | "                                |

TABLE 1 (Continued)

| D<br>mm | H<br>meters | v<br>m/sec. | t<br>°C | t'<br>°C | B<br>mm Hg | $\checkmark$<br>(cm <sup>2</sup> /sec.) |
|---------|-------------|-------------|---------|----------|------------|-----------------------------------------|
| 3.00    | 16.00       | 8.09        | 24.8    | 21.2     | 756        | .156                                    |
| "       | "           | 8.15        | "       | "        | "          | "                                       |
| "       | 18.04       | 8.11        | "       | "        | "          | "                                       |
| "       | "           | 8.11        | "       | "        | "          | "                                       |
| "       | 20.0        | 8.11        | "       | "        | "          | "                                       |
| 3.92    | 0.88        | 3.97        | 25.0    | 19.0     | 762        | .155                                    |
| "       | "           | 3.96        | "       | "        | "          | "                                       |
| "       | 1.36        | 4.81        | "       | "        | "          | "                                       |
| "       | "           | 4.83        | "       | "        | "          | "                                       |
| "       | 1.88        | 5.47        | "       | "        | "          | "                                       |
| "       | 2.38        | 6.04        | "       | "        | "          | "                                       |
| "       | "           | 6.02        | "       | "        | "          | "                                       |
| "       | 2.88        | 6.43        | "       | "        | "          | "                                       |
| "       | "           | 6.35        | "       | "        | "          | "                                       |
| "       | 3.39        | 6.81        | "       | "        | "          | "                                       |
| "       | 6.00        | 8.00        | 21.6    | 16.1     | 750        | .154                                    |
| "       | "           | 8.04        | "       | "        | "          | "                                       |
| "       | 9.00        | 8.65        | "       | "        | "          | "                                       |
| "       | "           | 8.62        | "       | "        | "          | "                                       |
| "       | "           | 8.58        | "       | "        | "          | "                                       |
| "       | 12.00       | 8.73        | "       | "        | "          | "                                       |
| "       | "           | 8.71        | "       | "        | "          | "                                       |
| "       | "           | 8.83        | "       | "        | "          | "                                       |
| "       | "           | 8.64        | "       | "        | "          | "                                       |
| "       | "           | 8.70        | "       | "        | "          | "                                       |
| "       | 15.00       | 8.78        | "       | "        | "          | "                                       |
| "       | "           | 8.77        | "       | "        | "          | "                                       |
| "       | "           | 8.77        | "       | "        | "          | "                                       |
| "       | 18.00       | 8.87        | "       | "        | "          | "                                       |
| "       | "           | 8.84        | "       | "        | "          | "                                       |
| "       | 20.00       | 8.88        | "       | "        | "          | "                                       |
| "       | "           | 8.84        | "       | "        | "          | "                                       |
| "       | "           | 8.82        | "       | "        | "          | "                                       |
| "       | "           | 8.88        | "       | "        | "          | "                                       |
| 5.04    | 1.0         | 4.24        | 25.0    | 19.0     | 762        | .155                                    |
| "       | 1.5         | 5.16        | "       | "        | "          | "                                       |
| "       | "           | 5.13        | "       | "        | "          | "                                       |
| "       | "           | 5.14        | "       | "        | "          | "                                       |
| "       | "           | 5.13        | "       | "        | "          | "                                       |
| "       | 2.0         | 5.82        | "       | "        | "          | "                                       |
| "       | 2.5         | 6.40        | "       | "        | "          | "                                       |
| "       | "           | 6.35        | "       | "        | "          | "                                       |
| "       | 3.0         | 6.85        | "       | "        | "          | "                                       |
| "       | "           | 6.92        | "       | "        | "          | "                                       |

TABLE 1 (Continued)

| D<br>mm | H<br>meters | v<br>m/sec. | t<br>°C | t'<br>°C | D<br>mm Hg | $\nu$<br>(cm <sup>2</sup> /sec.) |
|---------|-------------|-------------|---------|----------|------------|----------------------------------|
| 5.04    | 3.46        | 7.22        | 25.0    | 19.0     | 762        | .155                             |
| "       | "           | 7.17        | "       | "        | "          | "                                |
| 5.00    | 6.00        | 8.45        | 21.6    | 16.1     | 750        | .154                             |
| "       | "           | 8.45        | "       | "        | "          | "                                |
| "       | "           | 8.45        | "       | "        | "          | "                                |
| "       | 9.00        | 8.96        | "       | "        | "          | "                                |
| "       | "           | 8.96        | "       | "        | "          | "                                |
| "       | "           | 8.96        | "       | "        | "          | "                                |
| "       | 15.00       | 9.07        | "       | "        | "          | "                                |
| "       | "           | 9.28        | "       | "        | "          | "                                |
| "       | 18.00       | 9.20        | "       | "        | "          | "                                |
| "       | "           | 9.20        | "       | "        | "          | "                                |
| "       | "           | 9.20        | "       | "        | "          | "                                |
| "       | "           | 9.20        | "       | "        | "          | "                                |
| "       | "           | 9.35        | "       | "        | "          | "                                |
| "       | "           | 9.20        | "       | "        | "          | "                                |
| "       | 20.00       | 9.28        | "       | "        | "          | "                                |
| "       | "           | 9.25        | "       | "        | "          | "                                |
| "       | "           | 9.28        | "       | "        | "          | "                                |
| 6.19    | 1.00        | 4.33        | 24.0    | ---      | 762        | ---                              |
| "       | 1.50        | 5.24        | "       | ---      | "          | ---                              |
| "       | "           | 5.20        | "       | ---      | "          | ---                              |
| "       | 2.25        | 6.23        | "       | ---      | "          | ---                              |
| "       | "           | 6.20        | "       | ---      | "          | ---                              |
| "       | 3.00        | 6.85        | "       | ---      | "          | ---                              |
| "       | "           | 6.86        | "       | ---      | "          | ---                              |
| 6.10    | 6.00        | 8.58        | 21.6    | 14.6     | 750        | .154                             |
| "       | 9.00        | 9.15        | "       | "        | "          | "                                |
| "       | 12.00       | 9.35        | "       | "        | "          | "                                |
| "       | 14.00       | 9.38        | "       | "        | "          | "                                |
| 6.14    | 16.00       | 9.53        | "       | "        | "          | "                                |
| 6.05    | 17.20       | 9.15        | 22.8    | 20.3     | 764        | .153                             |
| "       | "           | 9.12        | "       | "        | "          | "                                |
| "       | "           | 9.21        | "       | "        | "          | "                                |
| "       | "           | 9.32        | "       | "        | "          | "                                |
| "       | "           | 9.17        | "       | "        | "          | "                                |
| "       | "           | 9.21        | "       | "        | "          | "                                |
| 6.14    | 18.0        | 9.30        | 21.6    | 14.6     | 750        | .154                             |
| 6.05    | 19.7        | 9.17        | 22.8    | 20.3     | 764        | .153                             |
| "       | "           | 9.23        | "       | "        | "          | "                                |
| 6.14    | 19.85       | 9.35        | 21.6    | 14.6     | 750        | .154                             |



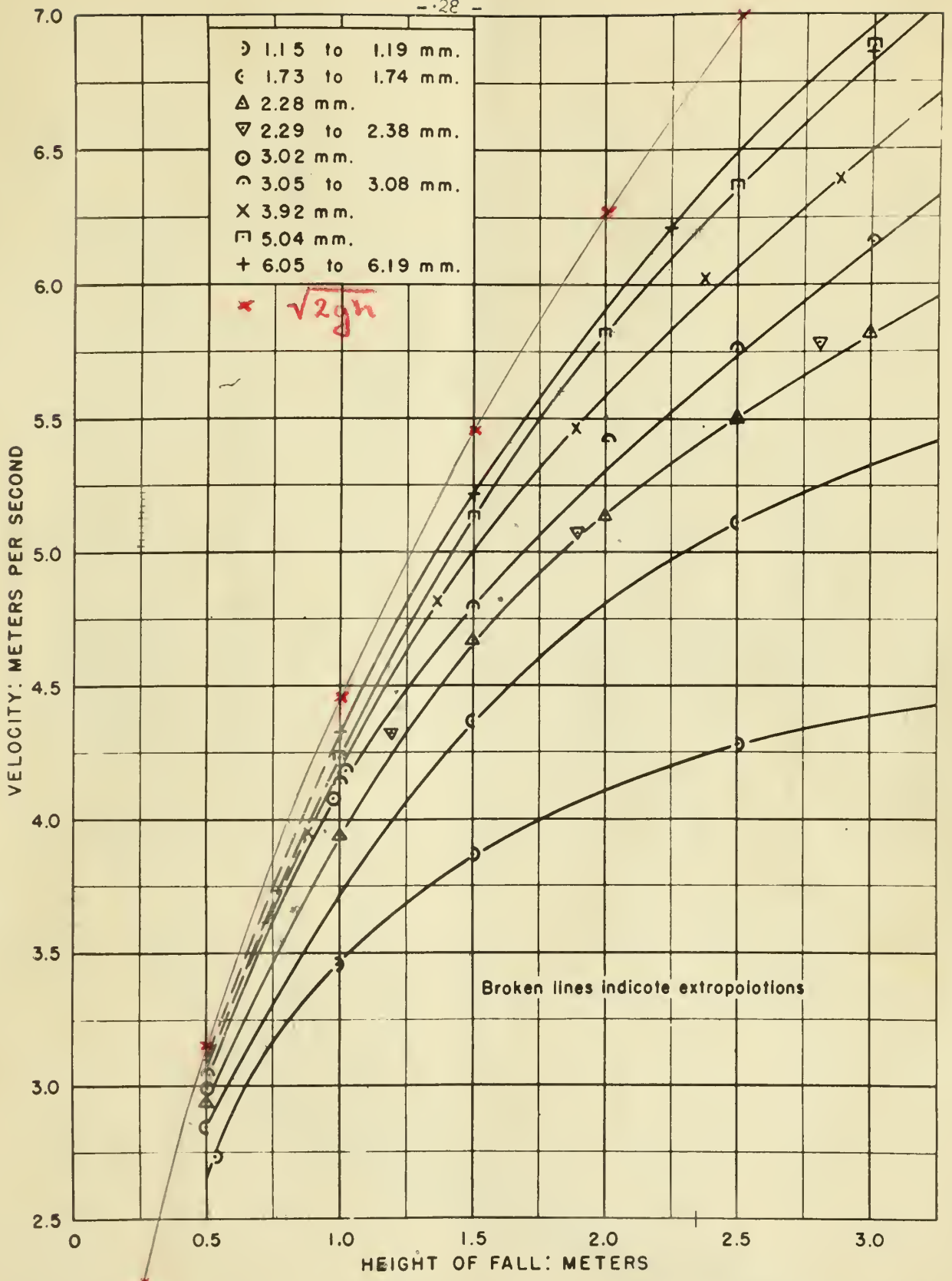


Figure 5a.- Velocity of fall of 7 sizes of waterdrops after heights of fall of from 0.5 to 3.0 meters.



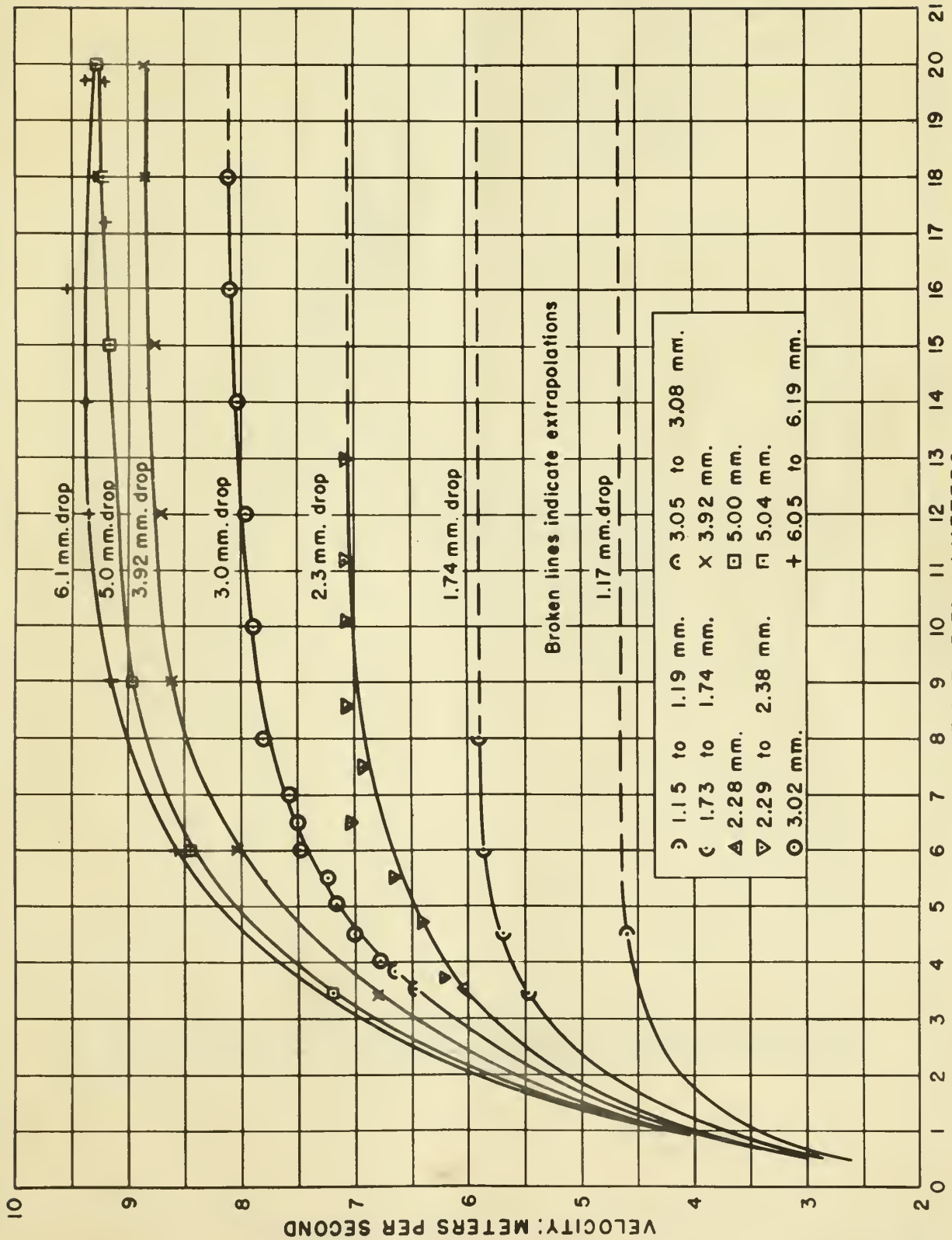


Figure 5b.— Velocity of fall of 7 sizes of waterdrops after heights of fall of from 0.5 to 20.0 meters.



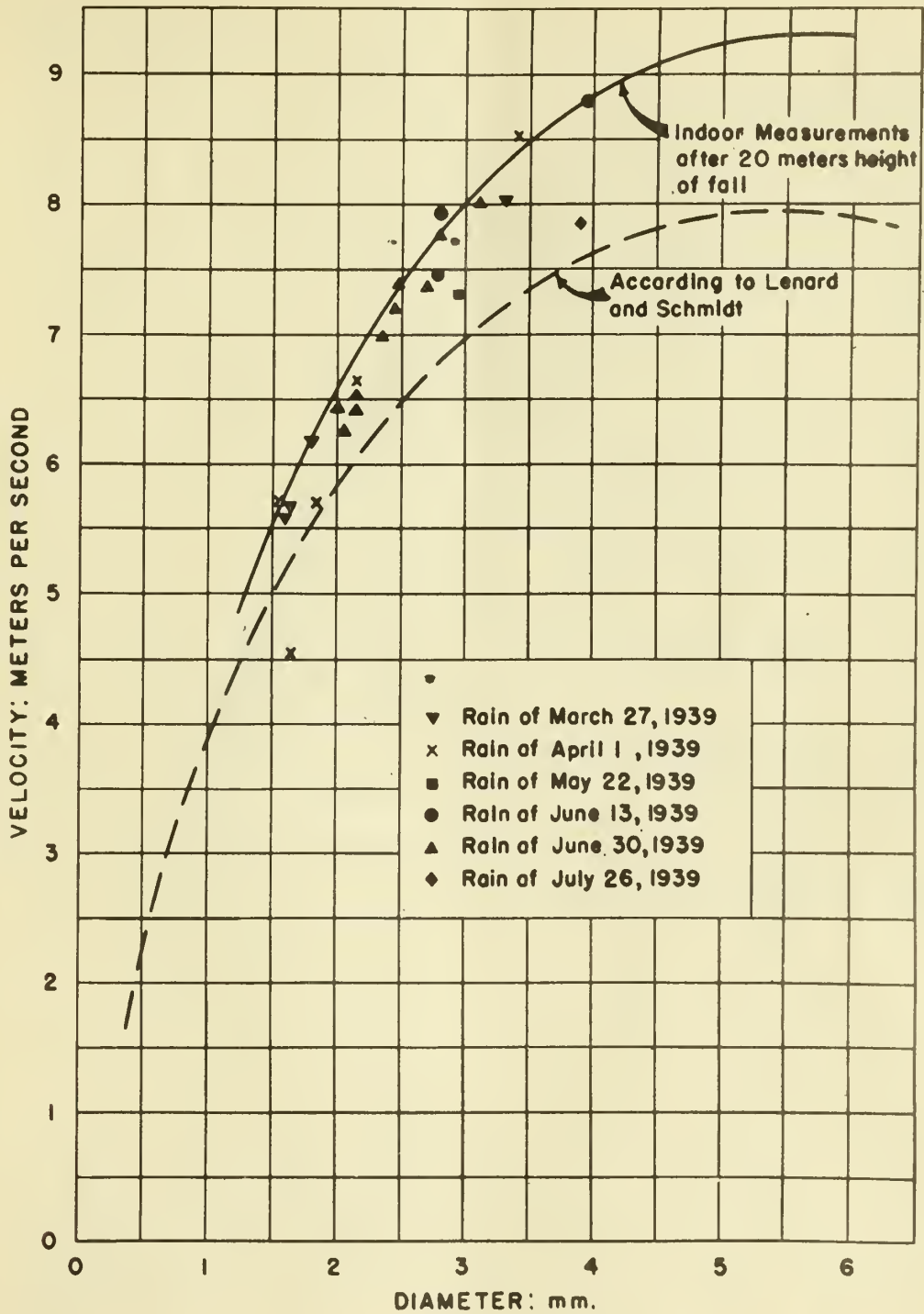


Figure 6.- Raindrop velocity data, together with curves showing the results of Lenard and Schmidt, and the results obtained with waterdrops after 20 meters fall.



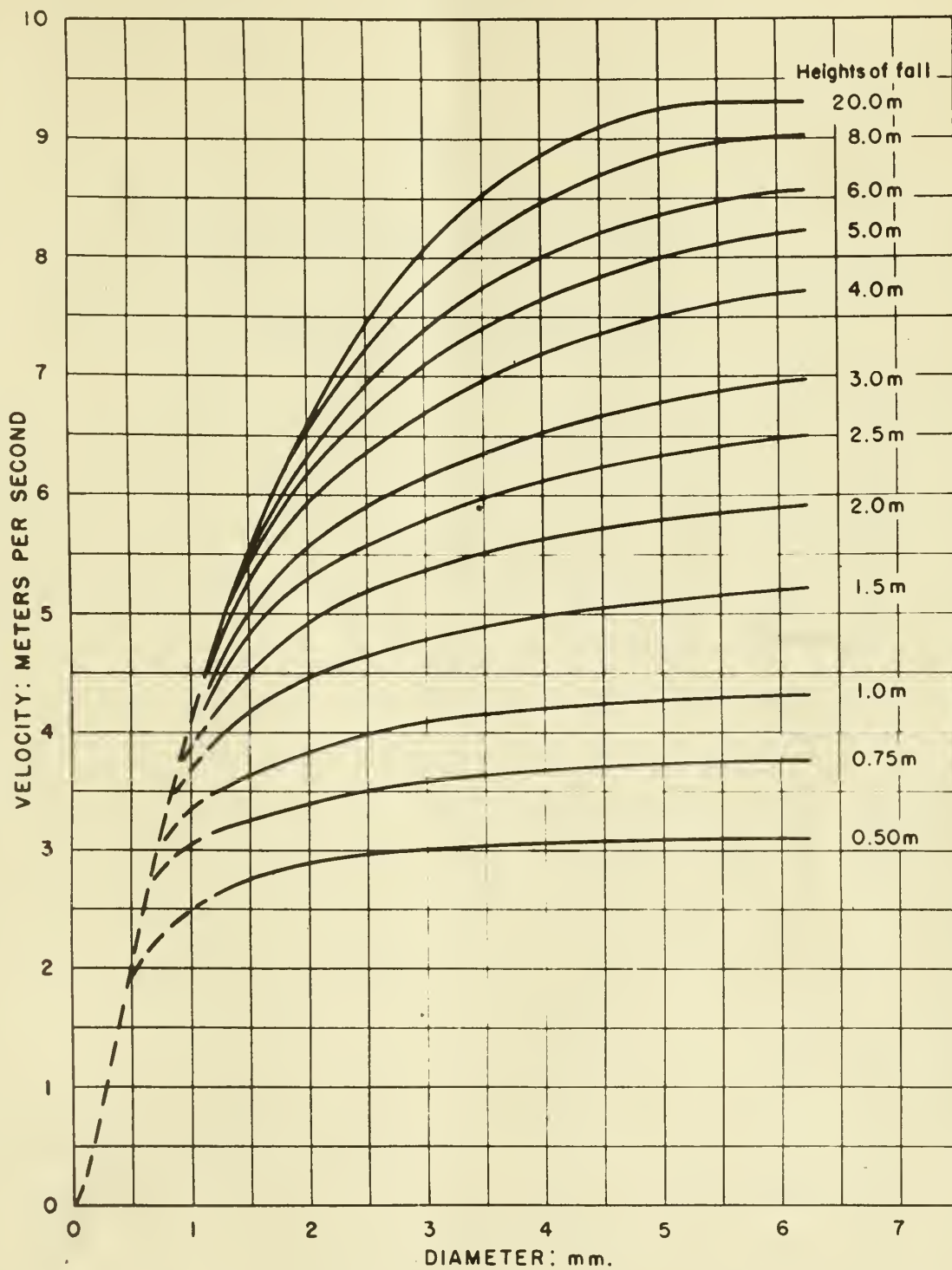


Figure 7.—Smooth curves showing the relation between drop diameter and velocity after 12 different heights of fall.



TABLE 2

Velocities of Falling Water-drops of Different  
Sizes After Various Heights of Fall

Velocity in meters per second; height of fall, H, in meters;  
diameter, D, in millimeters

| D<br>H |      |      |      |      |      |      |      |      |      |      |      |      |
|--------|------|------|------|------|------|------|------|------|------|------|------|------|
|        | 0.5  | 0.75 | 1.0  | 1.5  | 2.0  | 2.5  | 3.0  | 4.0  | 5.0  | 6.0  | 8.0  | 20   |
| 1.25   | 2.65 | 3.15 | 3.52 | 3.97 | 4.21 | 4.43 | 4.56 | 4.80 | 4.85 | 4.85 | 4.85 | 4.85 |
| 1.50   | 2.76 | 3.26 | 3.64 | 4.18 | 4.50 | 4.82 | 4.99 | 5.25 | 5.39 | 5.47 | 5.51 | 5.51 |
| 1.75   | 2.84 | 3.34 | 3.74 | 4.34 | 4.73 | 5.10 | 5.31 | 5.64 | 5.80 | 5.92 | 6.08 | 6.08 |
| 2.00   | 2.89 | 3.40 | 3.83 | 4.47 | 4.92 | 5.29 | 5.55 | 5.91 | 6.15 | 6.30 | 6.53 | 6.58 |
| 2.25   | 2.93 | 3.45 | 3.91 | 4.57 | 5.07 | 5.44 | 5.74 | 6.14 | 6.42 | 6.63 | 6.90 | 7.02 |
| 2.50   | 2.96 | 3.50 | 3.98 | 4.65 | 5.19 | 5.57 | 5.89 | 6.34 | 6.67 | 6.92 | 7.22 | 7.41 |
| 2.75   | 2.98 | 3.54 | 4.04 | 4.72 | 5.23 | 5.69 | 6.02 | 6.52 | 6.89 | 7.16 | 7.50 | 7.76 |
| 3.00   | 3.00 | 3.58 | 4.09 | 4.79 | 5.37 | 5.80 | 6.14 | 6.68 | 7.08 | 7.37 | 7.75 | 8.06 |
| 3.25   | 3.02 | 3.61 | 4.12 | 4.85 | 5.45 | 5.89 | 6.25 | 6.82 | 7.25 | 7.56 | 7.96 | 8.31 |
| 3.50   | 3.03 | 3.64 | 4.15 | 4.90 | 5.52 | 5.98 | 6.35 | 6.95 | 7.40 | 7.73 | 8.15 | 8.52 |
| 3.75   | 3.04 | 3.66 | 4.18 | 4.95 | 5.58 | 6.06 | 6.44 | 7.07 | 7.53 | 7.88 | 8.31 | 8.71 |
| 4.00   | 3.05 | 3.67 | 4.21 | 4.98 | 5.63 | 6.12 | 6.52 | 7.17 | 7.65 | 8.00 | 8.46 | 8.86 |
| 4.50   | 3.07 | 3.70 | 4.24 | 5.05 | 5.72 | 6.24 | 6.66 | 7.36 | 7.85 | 8.21 | 8.70 | 9.10 |
| 5.00   | 3.09 | 3.72 | 4.27 | 5.11 | 5.79 | 6.33 | 6.77 | 7.50 | 8.00 | 8.36 | 8.86 | 9.25 |
| 5.50   | 3.10 | 3.74 | 4.29 | 5.16 | 5.85 | 6.40 | 6.86 | 7.61 | 8.11 | 8.47 | 8.97 | 9.30 |
| 6.00   | 3.10 | 3.75 | 4.31 | 5.20 | 5.90 | 6.46 | 6.94 | 7.69 | 8.20 | 8.55 | 9.01 | 9.30 |



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